

INERTIAL GUIDANCE IN THE SPACE AGE

A basic study of inertial guidance for science students



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By Robert G. Brown
AC Spark Plug Division
General Motors Corporation
Milwaukee, Wisconsin

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One of the major miracles of modern technology is the development of completely automatic unmanned guidance and control of aircraft, missiles, and space vehicles. The rapid advance in guidance techniques has been a most important element in achieving a missile deterrent capability for the free world today.

Pilotless planes can now fly from one corner of the world to the other without the touch of a human hand, without regard for weather en-route, and without restriction as to the flight path.

Exciting potential has been added to the promise of conquering outer space, for with the increased accuracy of constantly improving guidance systems, vehicles can now not only be dispatched to other planets such as the moon, but can actually hit a pre-determined "crater" with precision.

There are many types of automatic guidance, but the newest of these is inertial guidance. In its simplest terms inertial guidance can be described as a type of guidance which is complete within itself. It needs no exterior energy radiating source to determine a course. It emits no signal and is not dependent on any ground equipment to operate. Other forms of guidance may be dependent upon waves of energy and a reference point either from the earth or other universal bodies such as the moon, the sun, or the stars.

Inertial guidance is especially advantageous in modern missile technology, because it sends no signal and receives no signal and thus cannot be "jammed" or intercepted or detected. It is not influenced by weather conditions. Missiles can be launched and guided accurately to the target with all corrections for winds, atmospheric conditions, and other factors automatically accomplished in flight.



Fig. 1

Guidance of a vehicle by pure inertial techniques requires only that you know precisely where you are at launch and precisely where you want your vehicle to go. The target point, incidentally, need not be limited to the earth, for the concept of inertial guidance can be used as effectively to guide a vehicle to a point in space. For that matter, inertial guidance can be used to navigate submarines while under water.

Three Basic Elements

To describe the basic principles of inertial guidance let's consider the three basic elements as related to a specific flight problem. The fundamental elements which you will note in the inertial guidance system are accelerometers, memory devices, and gyroscopes. Even the most sophisticated of inertial guidance systems today will have some counterpart to these basic elements.

Let us examine the components. First of all we must have an accelerometer. This device measures or detects the motion of the vehicle as it travels towards its destination.

The accelerometer is called upon to perform a Herculean task in speed measurement. Its range of measurement may vary from between eight-tenth thousandths (.0008) and ten (10.) G's. A "G" is a unit of measurement of acceleration used by engineers. It is equal to the force of gravity—that is, the acceleration imparted on a body by gravity if it is dropped in a vacuum. One "G" is approximately 32.2 feet per second per second.

To illustrate graphically the wide range of measurement which an accelerometer must perform (between .0008 and 10. G's), let us consider this example:

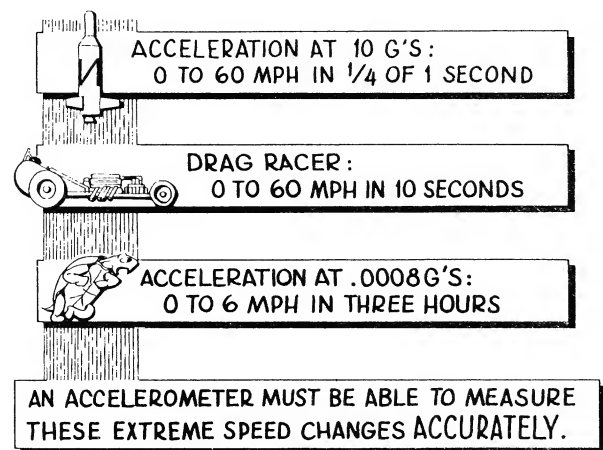
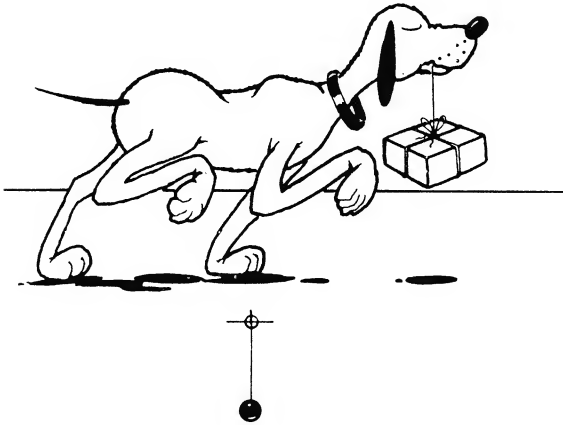


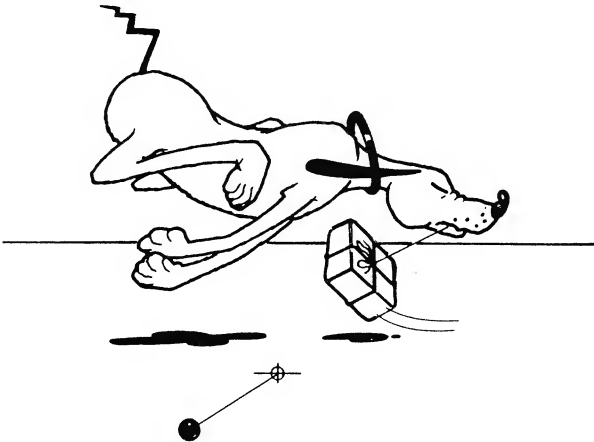
Fig. 2

A good drag racer, or hot rod, can accelerate from zero to 60 miles per hour in 10 seconds. If he accelerated at 10 G's, he would reach 60 in approximately one-quarter of a second. If, on the other hand, he accelerated at .0008 G's, three hours after he started to press the accelerator, he would have reached almost six miles per hour.

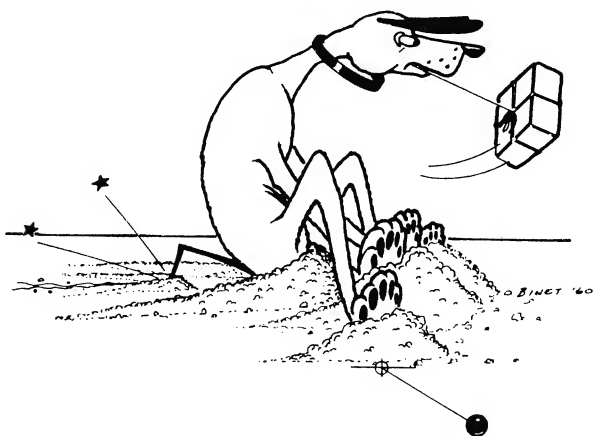
The manner in which the accelerometer operates can be illustrated by noting the phenomena of motion of a weighted string or pendulum. If you were to hold this string at arm's length and travel at a constant speed, the weight would continuously point directly down toward the center of the earth.



If you should suddenly increase your speed, then during the time of the increasing speed, the suspended mass would deflect backward. To de-



crease your speed would provide the opposite effect and the weight would continue forward. Thus, this pendulous activity exists only as long as speed is changing.



Pendulous Activity Measured

This activity can easily be measured. One can construct a simple speed change detector or acceleration meter (accelerometer) which does this. The direction of the pendulum motion indicates acceleration or deceleration, and the extent of speed change is reflected by the amount of angular deflection of the bob (weight).

In an inertial system which would guide a vehicle from Milwaukee to New York, we'll say, a more sophisticated version of the weighted string pendulum is used as an accelerometer.

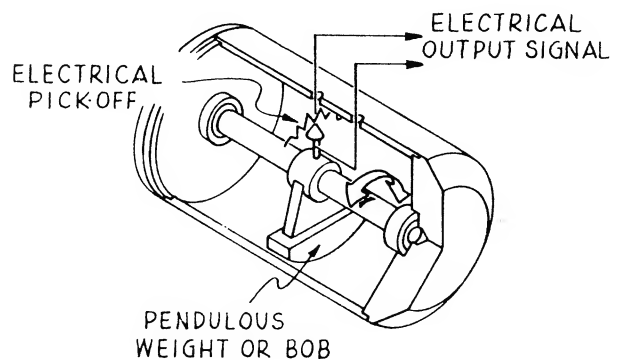


Fig. 3

In Fig. 3 you see a pendulous mass which will rotate when any speed change occurs. Attached to the pendulum is a contact arm which mechanically rotates with the pendulum. The angular rotation of the entire inner element produces electrical voltage proportional to the rotation. This voltage then is picked off by the wiper arm (tiny arrow). When no speed change is taking place, no electrical signal is generated. Any acceleration or deceleration causes the wiper arm to rotate and pick off a voltage proportional to the angular travel. Thus an electrical signal is available whenever a speed change takes place. The sense of the electrical signal will change depending on the acceleration or deceleration occurring.

In the typical inertial system two accelerometers are used. One measures speed changes along the desired course of flight, while the other measures lateral speed changes, that is, those left or right of the desired course.

Second Basic Element

The second basic element in the inertial system is the "memory" or integrating device. As its name suggests, this device "memorizes" the speed changes that have taken place.

The simplest memory device is an electric motor. The larger voltage there is applied to a motor, the faster the motor runs. The faster the motor runs, the more motor shaft rotations in a given length of time. The direction the motor turns depends on the polarity or sense of the applied electrical voltage.

Mechanical gearing is added to the motor so that a shaft turning at a lower speed than the actual motor shaft speed can be employed as the speed memory. In Fig. 4, Shaft A, coupled to the motor, drives shaft B through a gearing arrangement. Attached to shaft B is an electrical contact arm which rotates and develops an electrical signal proportionate to the memorized speed. With the wiper arm starting out at the bottom of the resistance element (right), the height it climbs shows the speed of the vehicle.

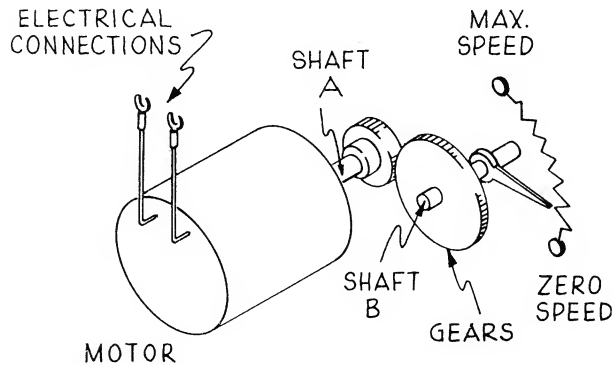
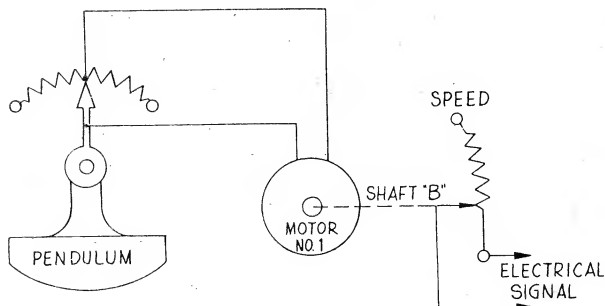


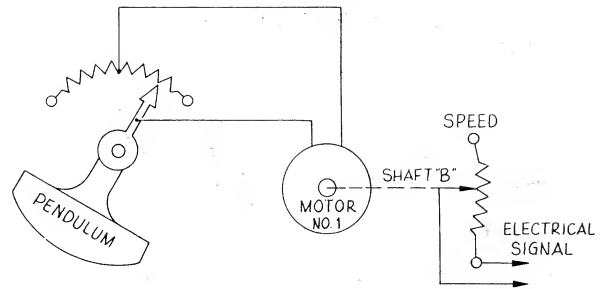
Fig. 4

To obtain an airborne speedometer we must combine the pendulum accelerometer and the simple motor memory device. In Fig. 5 is shown the manner in which these elements are connected. The pendulum registers zero in the pre-take-off position (Fig. 5-a) and the speed memory motor is stationary. In Figure 5-b is shown the pendulum position as the aircraft starts to gain speed. The acceleration produces an electrical signal which energizes the motor. The motor drives the wiper arm of shaft B along the resistance element. This resistance element is often called a potentiometer.



PRE TAKE-OFF CONDITIONS

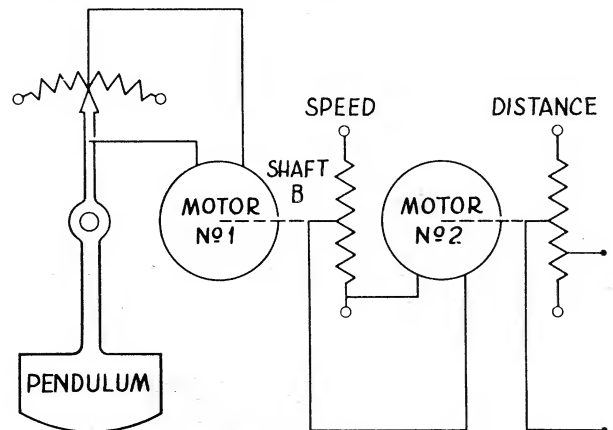
Fig. 5



SHORTLY AFTER START CONDITIONS

When the aircraft levels off, the pendulum returns to the "zero" position. The motor stops. The wiper remains in the position it has reached, thus recording and memorizing the ship's speed. As long as the aircraft neither accelerates nor decelerates, the wiper arm will remain in this position.

A second memory device will obtain for us the distance the aircraft has traveled. In figure 6 we see this second motor electrically connected to the wiper arm driven by Shaft B. As soon as voltage registers on the potentiometer, the second motor begins to rotate. This, too, drives a wiper arm up along another resistance element.



DISTANCE TRAVELED INDICATOR

Fig. 6

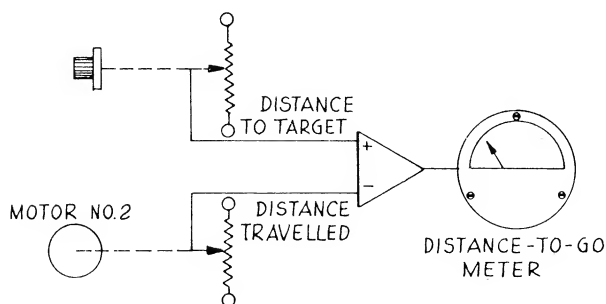
Notice that even though the pendulum has returned to "zero", denoting a constant speed, it has activated its potentiometer which in turn has activated Motor No. 2. The wiper arm of Motor No. 2 climbs along the distance potentiometer in accordance with the distance traveled. The distance memory motor will rotate at this rate until the aircraft speeds up or slows down, affecting the speed potentiometer.

Thus, we have used one memory device, coupled with the pendulum, to provide an airborne speedometer. A second memory device, working off the speed indicator, obtains for us the distance traveled.

Having the knowledge of the total distance to the destination, by using an additional "distance to destination" potentiometer, we can easily obtain the distance there is to go.

Continuous Indication of Distance

Figure 7 shows the normal connection of a manually adjustable "Distance to Destination" potentiometer and the "distance traveled" potentiometer. By appropriate connecting of these two channels of the electronic amplifier a continuous indication of distance to go can be displayed. The potentiometer signals are subtracted from each other within the amplifier. When the distance traveled and distance to destination are the same, the voltages from each potentiometer are equal, and the display meter will indicate "on target".



DISTANCE COMPARISON CIRCUIT

Fig. 7

We have seen thus far, how an accelerometer and two memory devices provide us with the speed and distance traveled in the direction in which the accelerometer is pointed. However, we know that in the normal flight of the aircraft, atmospheric conditions will cause the aircraft to roll, pitch, and yaw. In order for our accelerometers to function properly, we need a means of keeping the accelerometers properly oriented regardless of the aircraft's angular motions. The accelerometers must be stabilized.

This stabilizing function is provided by utilizing three gyroscopes mounted on the same mechanical platform as the accelerometers.

Gyros used in inertial guidance systems are nothing more than refined versions of a boy's gyroscopic top. These curious tops balance on the rim of a glass, or "walk a tightrope," or remain erect on the tip of a lead pencil.

The critical part of the gyroscope is the spinning wheel. The gyro cutaway shown in Figure 8 shows this wheel (A). An electric motor keeps the wheel spinning at a high rate—usually more than 10,000 revolutions per minute.

By attaching two small shafts (C) to the middle of each side of the frame (B) and adding a case (D), we have completed a basic gyroscope. The friction level where shafts (C) are supported must be kept extremely low for precise gyro operation. In fact, frame B is usually a complete cylindrical tomato can shape and is floated in a fluid to maintain a low friction level.

With the wheel running, if one were to rotate case (D) around the direction noted by the arrow (E), the wheel and frame (B) would be seen to rotate about shaft (C), the outer axis. Rotating case (D) in the opposite direction would produce the opposite direction of rotation about shaft (C).

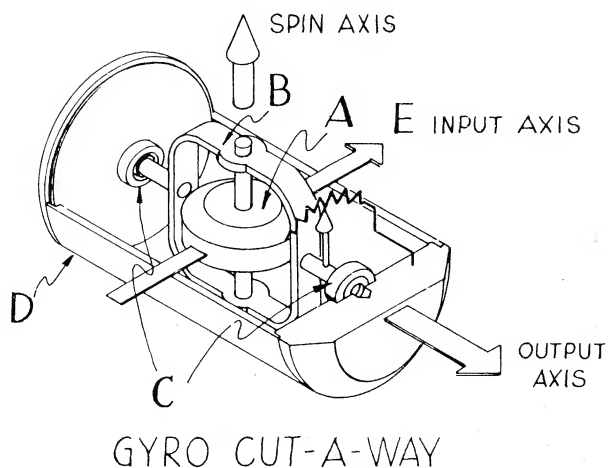


Fig. 8

Gyroscopic Phenomena

The gyroscopic phenomena exhibited here is that a rotation about an imaginary axis (E)—called the input axis of the gyroscope—will result in the gyroscope's wheel precessing about an axis (C) which is intersected at right angles to the original axis (E).

To utilize this gyroscopic principle in our guidance application, we merely attach frame D to

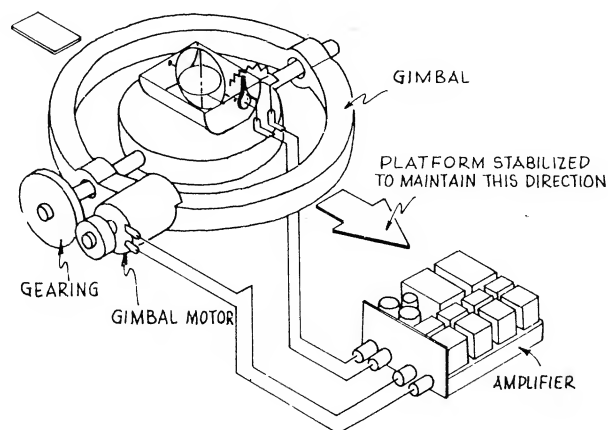


Fig. 9

the platform or base we want to stabilize (Fig. 9). Any rotation of the platform about the axis denoted by the arrow will result in gyro precession about the C bearings' axis.

Attaching an electrical pick-off system which would measure the precession angle (such as used in a memory device referred to previously), we could then produce an electrical signal which would increase as the precession angle increases. Thus we are able to measure the amount of rotation of a platform from a given orientation. As shown in Fig. 9, a zero electrical signal comes from the pick-off only when the wiper arm is at the center of the resistance element, and when the gyro spin wheel axis is normal to the stabilized platform.

The signal from the gyro is sent to an electronic amplifier and then supplied to a motor which is attached to an outer mechanical ring-like member, called a gimbal. This gimbal ring is a support frame that holds the platform.

Any rotation about the input axis will result in a precession of the gyro wheel. A voltage from the gyro pick-off will cause the gimbal stabilizing motor to drive and return the gyro to its zero precession angle. When the gyro pickoff is centered, the gimbal motor stops and we observe that the platform is back in its proper undisturbed orientation.

Thus, the gyro serves the purpose of remembering the original position of the platform on which it is mounted. In actual operation, we establish the desired platform position before the aircraft takes off, and we insure that the gyro wheel is centered for zero output at this position. The platform on which the gyro is mounted will remain in that position since any rotation will cause the gyro to precess and call for a gimbal motor to drive until the gyro has returned to its starting position.

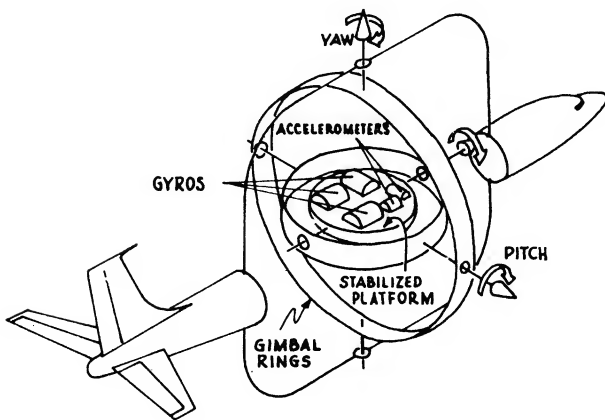


Fig. 10

Uses Three Gyroscopes

Since the aircraft may perform three different angular motions (roll, pitch, and yaw) at the same time, it is necessary to use three gyroscopes

es. Each gyro memorizes a single direction in space. These gyros must be mounted on a common platform, center of a cradle-like structure which allows the aircraft to go through its normal angular motions with a minimum of disturbance to the gyro platform.

The mechanical structure is completed by adding two circular rings, called gimbals, which surround the stabilized platform (Fig. 10). Motors are added for each additional gimbal ring.

Now, if we mount our two accelerometers together with the gyros on the central platform, the accelerometers will be stabilized from the undesired angular motions of the aircraft.

Thus, the basic inertial guidance system consists of a gyro stabilized platform carrying two accelerometers, four memory (integrating) motors, and three sets of electronic amplifiers. Today's engineer often sketches out the inertial guidance system in symbolic form, providing him with a kind of shorthand representation. This is called a block diagram and is shown in Fig. 11.

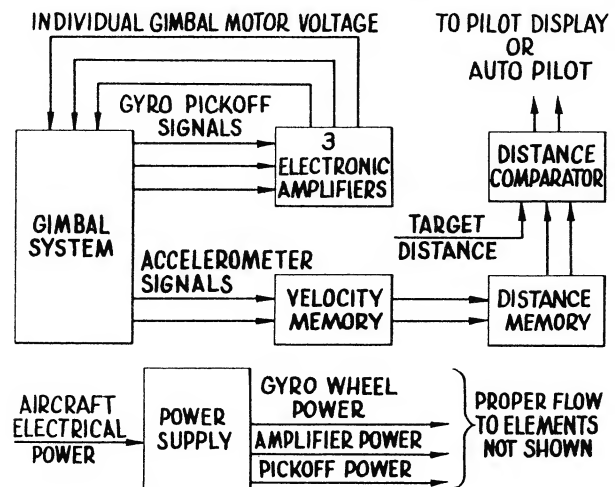


Fig. 11

The information which flows between blocks is labeled to provide a signal flow diagram.

Most inertial guidance systems consist of three basic functional elements: a gimbal system (often called the inertial measurement unit) which actually senses the aircraft's motions; a power supply, which provides the type, amount, and accuracy of electric power needed for all electrical equipment; and a computer, which includes memory integrators, distance computer, data displays and adjustments, etc. A number of technical refinements needed to completely describe an inertial guidance system have been omitted for the sake of brevity.

How Accurate Is Inertial Guidance?

A logical question at this point is just how accurate is an inertial guidance system. Since inertial guidance depends upon knowledge of the distance and direction to the target, any error in these will result in a corresponding target miss.

For example, supposing the actual distance to New York is 902 miles. If we, by some miscalcu-

lation, adjusted the distance to destination potentiometer to indicate that the distance is 904 miles, the guidance system will not indicate "on target" until we have overtraveled it by two miles. A direction error of about six-hundredths of a degree will result in a target miss of slightly less than one mile. (Fig. 12).

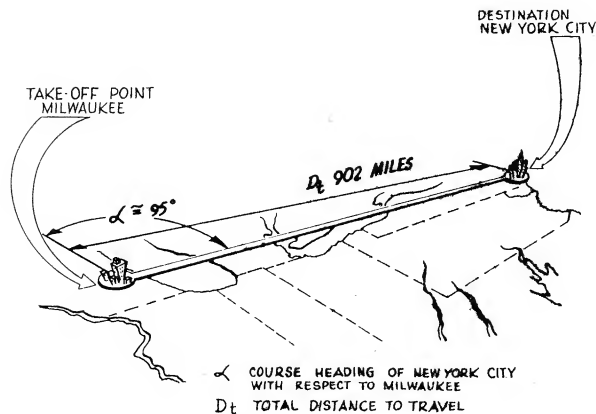


Fig. 12

The accuracy of inertial guidance is also dependent upon the quality of construction and assembly of the elements making up the guidance system. The most important of the factors in determining accuracy, and the only one discussed here, is the degree of perfection of mechanical balance within the gyros themselves.

So critical is the balance demand of the gyro that they are assembled under conditions ten times cleaner than those found in most hospital operating rooms. A speck of dandruff or a thumbprint on a finished gyro would cause enough unbalance to make it virtually useless in a guidance system and it would immediately be rejected.

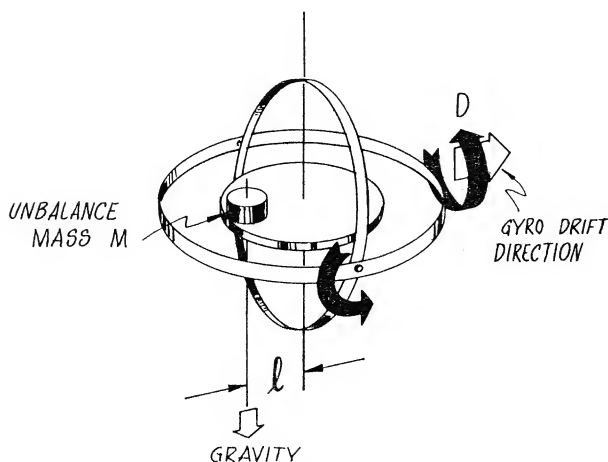


Fig. 13

As we stated earlier in the description of the role of the gyroscope, any precession of the gyro wheel about the unit's output axis is assumed to be due to an external disturbing aircraft motion. The platform is driven oppositely to correct this disturbance.

If, however, the gyro wheel or its support is not perfectly balanced, a small internal force results which causes the gyro to precess about this output axis. This rotational force can be visualized by reference to Fig. 13.

Gravity acting on the mass which is unbalanced tends to produce a torque (rotational force) which causes the entire float to rotate in a counter clockwise direction.

From basic physics we know that the unbalanced torque (ML) will result in a drift rate (D) which is proportional to the torque and inversely proportional to the angular momentum of the gyro wheel (H). The angular momentum depends upon the wheel speed and the physical size of the wheel.

Accuracy Highly Important

For a typical floated precision gyroscope, an unbalanced mass of approximately one hundred thousandths of an ounce, located a distance of three inches from the center of the float assembly will precess at about one minute of arc per hour. Thus, this minute particle of matter which is not even visible under a 30-power microscope, could result in an inaccuracy factor of one mile per hour. If two hours were required to fly from Milwaukee to New York with this quality of gyroscope, we would miss our destination by two miles.

Every precaution must be taken to insure near perfection in mechanical construction, cleanliness, and rigidity if high performance is required in a gyroscope. In assembling these gyros, employees work in clean rooms with rigidly controlled temperatures. The rooms are specially air conditioned to avoid dust particles. There is a complete change of air every four minutes, and the walls are a special surface which can be wiped clean with nylon cloths.

Workers wear special nylon shoe covers and dacron smocks which button to the neck and have no pockets to collect dust or lint. A dacron cap covers the head. Workers remove all jewels except wedding bands, and they wash their hands and dry them by air. Women may wear lipstick but no nail polish or powder which will flake.

These are only some of the precautions we know about now. Many new techniques, new materials, and new scientific frontiers are continually being explored to reach the ultimate in gyro perfection. These more perfect gyros will be used in the construction of long operating time, extremely compact and lightweight inertial devices for the next generation of inertial systems.

These will be the systems which will enable us to probe even further into the mysteries of the moon, Mars, Venus and all of outer space.

TYPICAL INERTIAL GUIDANCE SYSTEM

